Journal of Power Sources 264 (2014) 128–139

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Stationary and on-board storage systems to enhance energy and cost efficiency of tramways

M. Ceraolo, G. Lutzemberger*

Department of Energy, Systems, Territory and Constructions Engineering, University of Pisa, Largo Lucio Lazzarino n. 1, 56123 Pisa, Italy

HIGHLIGHTS

- One important bonus of tramways comes from the reversibility of electric drives.
- Braking energy of trams can be recovered in storage systems.
- High power lithium batteries and supercapacitors have been considered.
- Storage systems can be installed on-board or along the supply network.
- A simulation tool has been realised to achieve a cost/benefit analysis.

ARTICLE INFO

Article history:
Received 11 March 2014
Received in revised form
3 April 2014
Accepted 15 April 2014
Available online 26 April 2014

Keywords:
Energy recovery
Lithium battery
Railroad
Simulation
Storage system
Supercapacitor

ABSTRACT

Nowadays road transportation contributes in a large amount to the urban pollution and greenhouse gas emissions. One solution in urban environment, also in order to mitigate the effects of traffic jams, is the use of tramways.

The most important bonus comes from the inherent reversibility of electric drives: energy can be sent back to the electricity source, while braking the vehicle. This can be done installing some storage device on-board trains, or in one or more points of the supply network. This paper analyses and compares the following variants:

- Stationary high-power lithium batteries.
- Stationary supercapacitors.
- High-power lithium batteries on-board trains.
- Supercapacitors on-board trains.

When the storage system is constituted by a supercapacitor stack, it is mandatory to interpose between it and the line a DC/DC converter. On the contrary, the presence of the converter can be avoided, in case of lithium battery pack. This paper will make an evaluation of all these configurations, in a realistic case study, together with a cost/benefit analysis.

1. Introduction

The use of underground railroads and tramways has been recently rediscovered to reduce urban pollution and greenhouse gas emissions. In particular, aspects such as the lower moved mass per passenger and the higher well-to-wheel efficiency of the path between the primary energy source (e.g. a fossil fuel) and the wheels, in comparison to the standard gasoline or diesel cars, may show significant, beneficial effects.

Another important bonus of electric propulsion comes from the inherent reversibility of electric drives, that allow to send back the energy towards the electricity source, while braking the tram. This can be done installing the storage system on-board trains (*on-board storage*), or in one or more points of the supply network, typically in the vicinity of the substation (*stationary storage*). The first case has the disadvantage that the storage system must be replicated several times, since it has to be installed in all reversible trains, as well as the higher space occupation and the additional mass involved by this installation. In the second case, the main disadvantage is that

Abbreviations: ESS, electric substation; LFP, lithium iron phosphate; NMC, nickel manganese cobalt; OCV, open circuit voltage; RESS, rechargeable energy storage system; SOC, state of charge.

* Corresponding author. Tel.: +39 050 2217384.
E-mail address: lutzemberger@dsea.unipi.it (G. Lutzemberger).

http://dx.doi.org/10.1016/j.jpowsour.2014.04.070
0378-7753/

energy must flow through the contact line before reaching the stationary storage system and this causes energy loss and catenary voltage rise. When a train is far from the point in which the storage system is installed, the consequent voltage rise can require the train control to reduce the current conveyed to the line, to avoid excessive overvoltage. This might severely limit the amount of energy globally recovered during braking actions on the tram or underground railway. On the contrary, when two or more trains are very close to the stationary storage system, the latter requires to be properly oversized to manage the total amount of the braking currents. In literature, an overview about strategies and technologies to manage the braking energy in urban railroad systems is detailed in Refs. [1,2].

Furthermore, storage systems with several variants can be taken into account. Since the reduced braking times, the most frequently proposed solution takes advantage of supercapacitors, as described in Refs. [3,4]. From the other side, the recently developed high power lithium batteries make them more interesting and economically feasible than they used to be.

However, supercapacitors typically require the presence of the DC/DC converter, since the charge/discharge processes imply rather large voltage variations. When, on the contrary, storage system is constituted by a lithium battery, two variants can be considered: with and without DC/DC converter. The first one has the advantage to guarantee much more flexibility in the sizing of the storage system, limiting also the stress for the battery and deviation respect to the predefined state-of-charge (SOC). The latter has the advantage of the lower cost, although power fluxes and battery state-of-charge (SOC) cannot be explicitly controlled.

It must additionally be specified that the presence of the storage system on-board can also allow the tramway to operate autonomously, without the grid connection. Several other solutions equipped with sophisticated hybrid power train solutions, aimed to extend the range during driving in absence of the grid, are actually under investigation [5,6].

This paper, by means of a simulation model, makes a comparison of all the variants, in a realistic case study. Some detailed conclusions will be drawn from the analysis, mainly in terms of energy saving, sizing and cost evaluation for the considered storage systems.

2. The system under study

The basic structure of the system under study is a traction line, fed by electrical substations, with trams that start, accelerate, run, and brake. The frequent brake applications cause a large amount of kinetic energy to be zeroed, either by converting it into heat or, much better, by converting it back into electricity and using it for some useful task.

The most natural way to reuse this energy is either to send it back into other trains that need it or to store into some storage means. The situation is depicted in Fig. 1 and Fig. 2. In Fig. 1 the braking energy from train A is sent into train B, while in Fig. 2 it is partly sent into B, partly stored in the storage system located around ESS2. The next paragraphs present the main characteristics of the system under study, considering electric substations, network, trams.

The energy flows analysis requires a simulation tool able to simulate the network equations, the vehicle dynamic equations, the driver, and different running phases, such as acceleration, constant speed run, coasting and braking. The model has been developed in Modelica language [7–9]. A simplified version, containing only four substations and four trams, is shown in Fig. 3. As visible, the main subsystems are the electrical substations, the contact line, the trams and the storage system (in figure only one stationary storage system

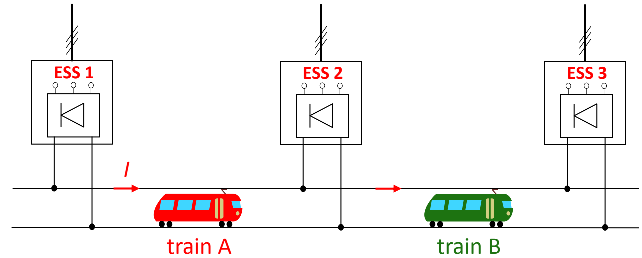

Fig. 1. A simplified representation of the traction line. Train A is braking and B is partially absorbing the recovered braking energy.

in correspondence to ESS3 is displayed). The blue lines represent electric wires, while the dark blue and the pink ones represent a bus signal that transfer information as the position, direction and velocity of the trams to the subsystem simulating the contact line. Further details about Modelica language characteristics and modelling technique used are reported in Ref. [10].

2.1. Electrical substations and contact line

Tramline feeding substations are typically based on diode bridges. Very common is the situation in which two three-phase bridges are present, fed by different windings of three-winding transformers: if the two windings are star and delta connected, and the number of secondary turns are suitably chosen, in this case each substation operates as a twelve-pulse DC source. Since it is out of the scope of this study to evaluate effects of harmonics, only the DC component of this source is of interest, and therefore for any substation the well-known DC equivalent of Fig. 4 is used, in which R_{fict} is a fictitious resistor that simulates the voltage drop due to the commutation phenomenon [11]. The main characteristics of the ESSs are summarized in Table 1.

Since during simulation trains move along the line, the contact line is a time-varying system. The line resistance between a train and the subsequent one varies over time; moreover, when a train moves from a section to another, the very topology of the contact line is changed. It is possible to analyse the contact line in reference to the scheme reported in Fig. 5, related to bilateral power conditions. Indeed, the line resistance can be modelled as variable linearly along the line, according to the following expressions:

$$\begin{aligned} R_1 &= (1-\delta)R_{tot} \\ R_2 &= \delta R_{tot} \\ \delta &= \frac{(P_2 - x)}{L_{12}} \end{aligned} \tag{1}$$

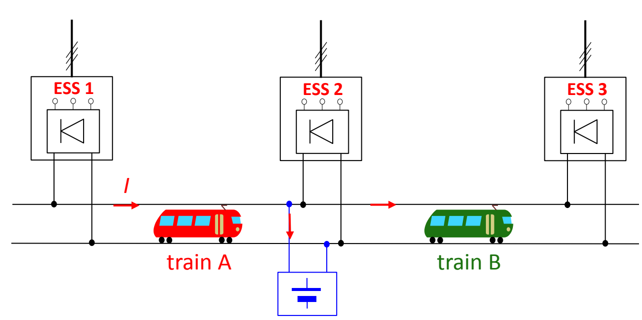

Fig. 2. A simplified representation of the traction line. Train A is braking and a storage system helps train B in absorbing the recovered braking energy.

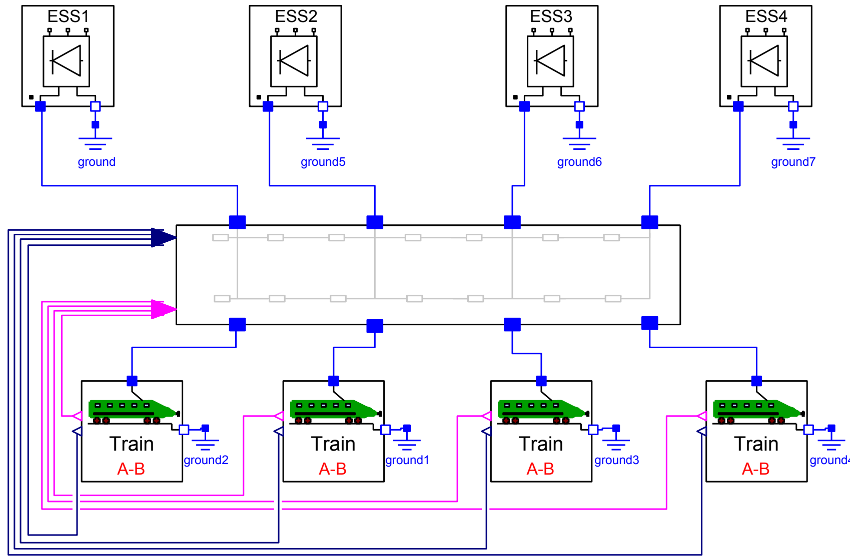

Fig. 3. Simplified version of the developed model.

where:

- R_1 is the left side line resistance.
- R_2 is the right side line resistance.
- δ is the ratio of the distance between the train and ESS2 positions to the distance between ESS1 and ESS2.

About modelling technique, the complexity to implement a time varying systems can be dealt with the creation of new components, that aim to compute the correct values of the variable resistors as well as the variation of the topology of the line. Further details of the contact line simulation model are described in Refs. [10,12].

2.2. The storage systems

The proposed storage systems have been modelled by the usage of equivalent electrical networks. About electrochemical storage, a general structure is here proposed: it allows different degrees of precision, depending of the number of R–C blocks used. Fig. 6 reports a general representation of the electrical model. Following remarks can be done:

- The number of n-blocks can also be equal to zero: the circuit is therefore reduced to the only electromotive force E with internal resistor R_0. Increasing the number of blocks the precision becomes higher, but also the difficulty to identify all the required parameters, typically functions of the state of charge.
- The resistor R_p can assume a variable value, according to the applied voltage. This element models the coulombic efficiency of the storage, representing parasitic reactions responsible of internal losses. This approach, commonly used also in the past, for other battery typologies, is also described in Refs. [13,14].

A model where n is equal to zero has been used. The capacitance is very large, and is able to simulate the electromotive force of the battery as a linear function of SOC. Resistance R_p is tuned in such a way that the cycle efficiency is realistic, typically 90% with lithium cells. The parameters and their dependency from SOC can be easily determined by some basic experimental tests, of the type described in Ref. [15].

A similar approach has been followed for supercapacitors: literature presents several structures, i.e. the general model composed by three branches and reported in Ref. [16]. In case of no interest in considering the slow dynamic of the device, except the main charge/discharge process, a simplified representation reported in Fig. 7 can be adopted.

It is also significant to observe that the following representation is equivalent to that one already chosen for the battery. Additionally, to correctly represent the coulombic efficiency, the presence of an additional stray current branch of the type already used for the battery can also be considered. Finally, Also in this case the parameters can be determined by some experimental tests: the procedure has been adopted to set the correct parameter values inside the simulation model.

2.3. The DC/DC converter

As already mentioned, the presence of the DC/DC converter is strongly recommended in case of supercapacitors to fully exploit their large window voltage. It is also useful to protect the storage from extra stress, reducing the peaks of charge/discharge current, or control SOC along time. The converter can be represented by

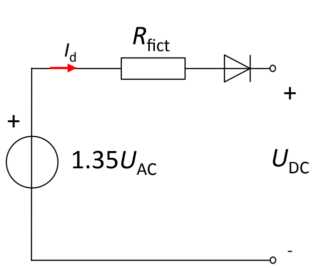

Fig. 4. Simple algebraic-DC component equivalent of ESSs.

Table 1
Main characteristics of the ESS under study.

ESS characteristics	
No-load voltage (V)	796
Nominal power (kW)	1800
Nominal current (A)	2400

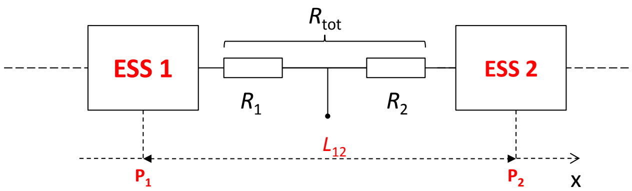

Fig. 5. Modelling of the line resistance.

means of algebraic equations, considering internal losses as function of the drain current. The output current is determined by the power requests from the load, with two additional terms to take into account the voltage regulation and the SOC control needs, as above explained. The general structure of the adopted DC/DC control logic is reported in Fig. 8.

2.4. Trains with drivers

Modelling of trams requires modelling the train's traction system, the resistances to its movement, the driver's behaviour.

2.4.1. Power train

In actual trains, the set point from the driver is sent to the inverter controlling the tram electric drive as detailed in Fig. 9. Basically, since transients do not impact significantly, the electric drive is simulated algebraically. Inner details of voltages and currents inside are not very important, and the detailed dynamics of the three-phase machine and its power converter can be neglected. Electric drive is therefore modelled as a system able to produce the tractive force as required by the driver generating some power losses, expressed as a function of the mechanical speed and the required force. In this regard, an efficiency map can also be derived: it can be referred to the whole chain, from the contact line to the wheels, both with the maximum allowed limits for the electric drive, in terms of maximum traction and braking force versus the vehicle speed [17]. Of course, the braking force can also be increased considering the additional dissipative braking on resistors on-board trams.

As noticed, one important characteristic of the electric power train is their reversibility. Therefore a negative torque can be requested to the electric machine, that causes the mechanical power to be reversed. This way, power is sent back to the catenary, under the assumption that the electric system is able to use this power in some way. However each train must avoid feeding power to the catenary when this would cause the line voltage to become too large, therefore a controller of the DC power (when directed upstream) must be implemented for this purpose. This can be a simple controller that acts only when the voltage tends to overcome the maximum allowed limit: the excess power is therefore dissipated on resistors on-board trains. This action can be

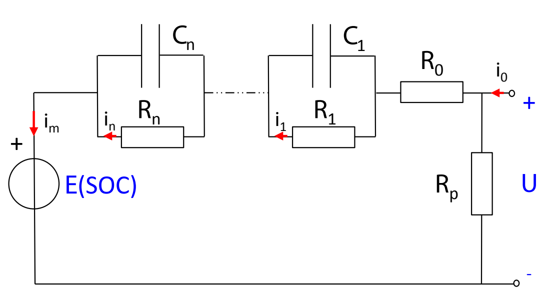

Fig. 6. General model for the electrochemical cell.

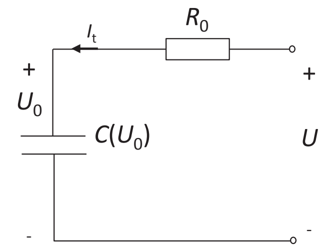

Fig. 7. General model used for the supercapacitor.

performed in two different ways by the presence of a spillway power device, on-board trains:

- Without any kind of modulation of the braking power conveyed along the catenary. In this way the voltage reaches immediately its limit, and the energy recovery is cut. All the braking power is dissipated on resistors on-board trains.
- By modulating the braking power conveyed along the catenary, to avoid to reach instantaneously the upper allowed limit. This can guarantee an extended recovery of energy.

The main characteristics of the trams are finally summarized in Table 2. The shown empty mass does not take into account any kind of on-board storage device, whose mass requires to be added apart.

2.4.2. Resistance to movement

This can be effectively modelled using the usual formula summing-up aerodynamic drag and rolling resistance:

$$R = mg(f_r \cos\alpha + \sin\alpha) + AV + BV^2 \quad (2)$$

where:

- R is the force the object opposes to movement (so directed against the vehicle movement).
- α is the angle between track and horizontal plane (measured positive when the vehicle moves uphill).
- m is the vehicle mass.
- f_r is the rolling coefficient for wheel to track contact.
- A and B are an empirical positive numbers that take into account the front and lateral resistance to train movement.
- V is the vehicle speed (absolute value).

It must be finally said that when the vehicle is standstill at a relatively high slope, some positive external force must be exerted

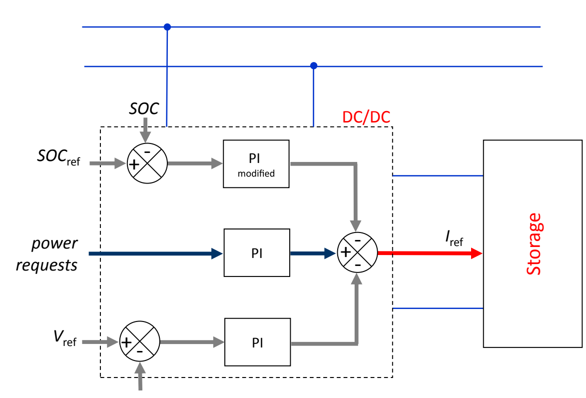

Fig. 8. Control logic for the DC/DC converter.

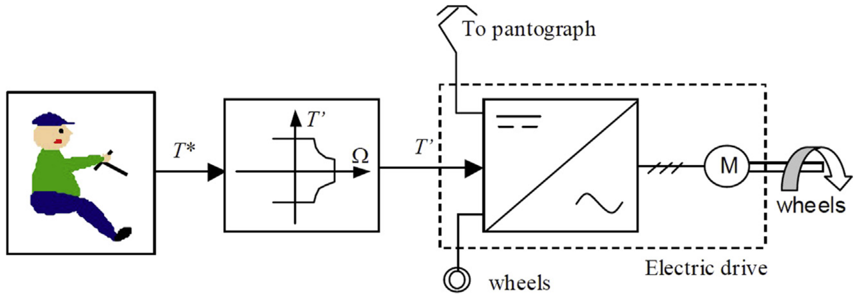

Fig. 9. Interaction between the driver and the electric drive.

on brakes to avoid unwanted movement. However this force is generated by mechanical brakes, to avoid energy losses connected to electric braking.

2.4.3. Driver

A different paradigm for modelling drivers is needed, considering that rail driving contains coasting in which the speed profile is not known in advance, and rail tracks contain blocks that require satisfying of space versus time constraints. In this regard, a state machine formed by the following steps has been defined:

- acceleration up to a reference speed; when this speed is reached commutation to next phase.
- constant speed until a predefined distance to the next block end; when this distance is reached commutation to the next phase.
- coasting, up to the braking distance to the next block end; when this distance is reached commutation to the next phase.
- braking at the deceleration required to safely stop by the block end. Therefore the deceleration might change during braking depending on unexpected events such as small slope changes.

During braking, a speed control loop is activated, in which the speed is function of the train's position, according to a constant deceleration parabola curve, as happens actually on-board trains [17].

3. Results

3.1. The application

The considered case study refers to a real tramline located in the northern part of Italy (Bergamo). The total line length is about 12 km, and composed by 10 Substations (ESSs). As noticeable from the line timetable, the number of the operating trams is variable respect to the trip frequencies, divided in rush hours (10 trains), low load hours (5 trains), holidays (3 trains). Also position and speed of the trams along the path are always referred to real operating conditions. The actual path slope is considered in simulation, but it does not have a significant impact on results.

Table 2
Main characteristics of the trams under study.

Tram characteristics	
Empty mass (t)	41.9
Load mass (t)	17.4
Max power (kW)	628
Max voltage (V)	900
Nominal voltage (V)	750
Min voltage (V)	500

When no storage systems are installed on the feeding system, the tram can effectively recover braking energy only when other trams are present and are adsorbing power, in the vicinity of the considered tram itself. It is indeed expected that when some energy storage is installed along the line or on-board tram, energy recovery during braking can be enhanced. In fact, even when no enough load is present to adsorb energy from trains that are braking, the storage system can adsorb it, and deliver it at a different time, when enough load is present. The analysis of the results was performed with the objective of evaluating the energy saving, the sizing and the installation costs of the storage systems for all the variants here summarized:

1) Stationary systems.
   - Systems based with supercapacitors, interfaced with the line by means of DC/DC converters.
   - Systems based with high power lithium batteries, interfaced to the line with or without the DC/DC converter.
2) Systems on-board trams.
   - Systems based with supercapacitors, interfaced by means of DC/DC converters.
   - Systems based with high power lithium batteries, interfaced with or without the DC/DC converter.

For simplicity, the storage system dimensioned for the stationary application has been left unmodified for the case of on-board installation. In this way, it becomes therefore possible to compare different energy flows, and the corresponding energy saving under equal terms, helping the reader to clearly understand strengths and weaknesses for the two solutions.

The simulations of rush, low load and holiday hours have been repeated for the different analysed configurations. The effective combination of the hours typology for one typical year, provided by the tramway operators, was also taken into account: indeed school working days, no-school working days and holidays, each one

Table 3
Rush, low load and holiday hours during one typical year.

Month	Rush hours	Low load hours	Holiday hours
January	75	282	163
February	100	240	130
March	75	265	179
April	105	252	146
May	110	264	146
June	45	295	163
July	0	391	130
August	0	340	179
September	50	290	146
October	115	276	130
November	105	252	146
December	50	290	163

characterised by its own combination, have been considered. The total number of hours during the year, divided for typology, is visible in Table 3. Results have been accordingly analysed in terms of annual energy flows from the substations, from and to the trams, from and to the storage systems.

More in detail, the following nomenclature will be adopted:

- ESS energy is referred to the energy flows from sub-stations. The energy fluxes are not reversible.
- RESS energy is referred to the energy exchanges with the storage systems.
- Recovered energy is the energy fed on the grid during braking, that can moves to the other trams, or to the storage system. It can be considered as the share of the braking energy not dissipated on resistors on-board trains.
- Losses are referred to the energy losses along catenary, or due to the charge–discharge efficiency of the storage system.
- Energy saving is evaluated on the basis of ESS energy variation respect to a target configuration, typically the configuration without any kind of energy recovery, in which all the braking energy is dissipated on the resistors on-board trains.

3.2. Stationary systems based with high power lithium batteries

The first case is related to the installation of a stationary lithium battery pack, linked to the line with or without the presence of the DC/DC converter. As already noted, the first solution has the main advantage to guarantee much more flexibility in the sizing of the storage system, limiting also the stress for the battery and deviation respect to a predefined SOC. The latter has the advantage of the lower cost, although power fluxes and battery SOC cannot be explicitly controlled.

3.2.1. Configuration without the DC/DC converter

Results related to the configuration in which the storage is directly connected to the grid without the interposition of the DC/DC converter were detailed in Refs. [12,17]. For clarity, Table 4 shows the some basic parameters of the battery: the number of the cells must be chosen in such a ways that when the contact line is at its nominal voltage the SOC stays at an intermediate level, and the nominal capacity is in agreement to the maximum allowed current stress. A solution based on NMC cells [18] expressly dedicated for high power applications, able to withstand the maximum performance declared by the manufacturer, is for instance adequate.

The proposed usage of lithium batteries might rise concerns about the cell life. However, the SOC oscillation during charge–discharge cycles is around 4% in case of rush hours. The fluctuation may also decrease to 1–2%, considering low load hours or holidays. Even though no clear evidence exists in literature, experiences made by the authors [19] and some available manufacturer's indications [20], shows that the battery life corresponding to such micro-cycles is around several hundreds of thousands, thus allowing the hypothesis that the battery in this application can reach the end of its calendar life, estimated in ten years.

Table 4
Main characteristics of the battery pack, stationary configuration without the DC/DC converter.

Battery (NMC cells based)	
Number of cells	220
Nominal cell voltage (V)	3.7
Nominal voltage (V)	814
Nominal capacity (Ah)	100
Peak current p.u. of C_n (A/Ah)	10
Nominal energy (kWh)	81.4

3.2.2. Configuration with the DC/DC converter

Although the presence of an additional component may result disadvantageous in terms of space occupation and complexity for the whole system, the introduction of the DC/DC converter between the storage system and the grid can guarantee much more flexibility in the sizing of the storage itself, being the battery voltage not directly constrained to the operating grid window voltage. Additionally, as already noted, SOC can be directly controlled imposing a reference value, and the battery current limited to its safety value. These facts can help to increase the battery life, indeed the presence of the DC/DC converter is rather recommended. This is because this configuration will be used as reference later. The storage system is changed as shown in Table 5. Here the previous solution based on NMC cells has been replaced with a more cost effective technology.

On the other hand, the introduction of the DC/DC converter implies a reduction in terms of energy saving, due to its losses [17]. Fig. 10 shows the action run by the DC/DC converter for the voltage regulation, having as reference the line voltage of 800 V, the battery current limitation, reduced to 1000 A under indication of the manufacturer, and the SOC balancing having as reference 50%.

From the economical point of view, it can also be said that the reduction of battery cost due to the different technology (i.e. LFP instead of NMC) should be able to cover the extra-cost for the DC/DC converter. Further details about costs are reported in paragraph 5.

3.2.3. Energy saving

The energy saving has been evaluated on several conditions, following explained:

A. Trams dissipate all the braking energy in on-board resistors.
B. Trams send their braking energy into the catenary as long as the catenary voltage does not overcome the maximum limit of 900 V.
C. As per case B, but with addition on *n*-storage systems having the previously mentioned characteristics, in correspondence to the ESSs situated along the tramline route (C-1 to C-10).

Cases B and C can be implemented according to two controls actions:

- *Baseline*. In this case braking energy is sent into the catenary as long as the local voltage is within limits (for our application 900 V); As soon as the voltage reaches this limit, recovery is stopped.
- *Advanced*. In this case when the contact line voltage reaches 900 V the energy recovery is not stopped, but reduced to exactly

Table 5
Main characteristics of the battery pack, stationary configuration with DC/DC converter.

Battery (LFP cells based)	
Number of cells	190
Nominal cell voltage (V)	3.2
Nominal voltage (V)	608
Nominal capacity (Ah)	160
Peak current p.u. of C_n (A/Ah)	6
Nominal energy (kWh)	97.3
Cell mass (kg)	5.6
Battery pack mass (kg)	1277

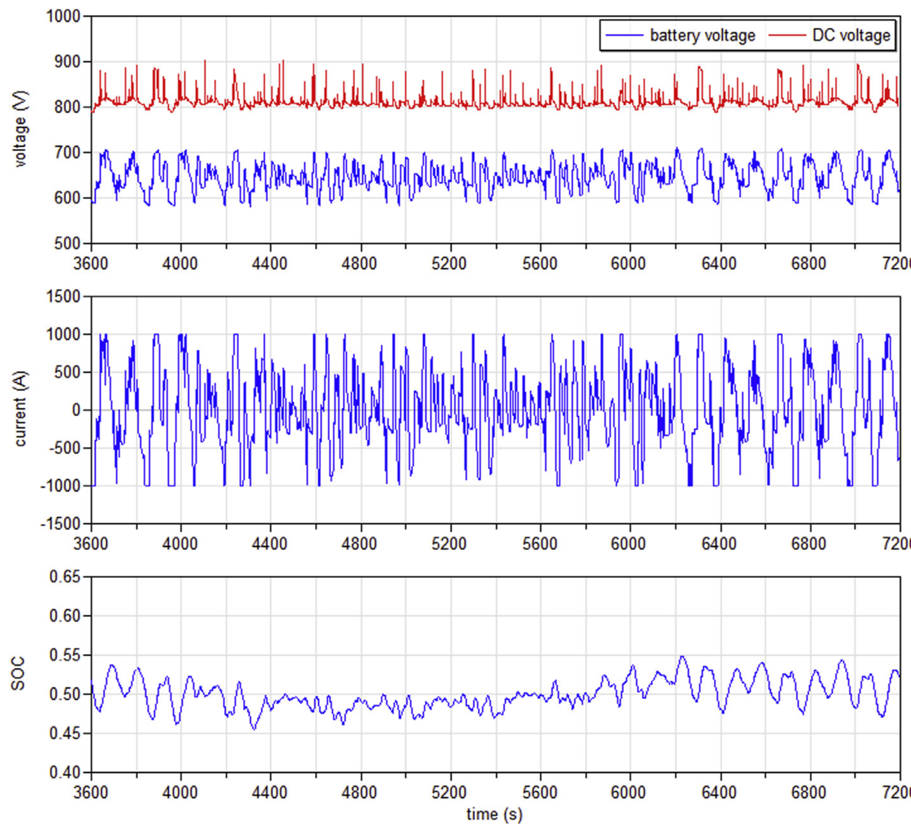

Fig. 10. Input and output voltage of the DC/DC converter (top), battery current (middle) and SOC during rush hours (bottom).

the amount that allows this limit not to be exceeded. In case there are trains accelerating or running, this control allows significant amounts of energy to be sent to them.

The two control strategies involve different levels of the supply energy from ESSs, that is significantly reduced in case of the advanced control respect to the baseline one. Indeed the recovered energy on the grid can be enhanced [17].

In this regard for all the examined conditions the "Total ESS Energy", i.e. the total energy absorbed by the railroad summing up the absorptions of all the ESS's, and the "Recovered energy", i.e. the total flow of energy recovered into catenary by trains, are shown in Table 6.

As already observed the system includes a DC/DC converter among the battery and the grid. Reduction in terms of energy saving due its application, considering suitable current limitation for the battery, is on average around 5% respect to the direct connection to the grid [12,17].

Table 6
ESSs energy and recovered energy in case of stationary configuration with DC/DC converter.

Case	Total ESS energy (MWh/y)		Recovered energy (MWh/y)	
	Baseline control	Advanced control	Baseline control	Advanced control
A	3100		0	
B	2869	2497	206	742
C-1	2777	2126	394	1280
C-2	2541	1896	699	1491
C-3	2152	1801	1156	1590
C-5	1875	1762	1415	1608
C-10	1739	1757	1508	1614

As visible, an increase in the energy recovered does not automatically translate in a reduction in the energy absorbed by the railroad, since this recovered energy must transfer from the braking train into the one using that energy, this producing additional loss during this transit along the catenary. This is visible also from the sum of the recovered energy plus the total ESS energy for cases B and subsequent, that is slightly higher than the total ESS energy of case A.

Furthermore, Fig. 11 shows the trend of the energy saving versus the number of the storage units installed. The energy saving strongly increases moving from one to the three storages configuration, on the contrary for the extra storage systems the level of the energy saving tends to an upper limit, so that the additional capital costs are not balanced by the extra energy saving.

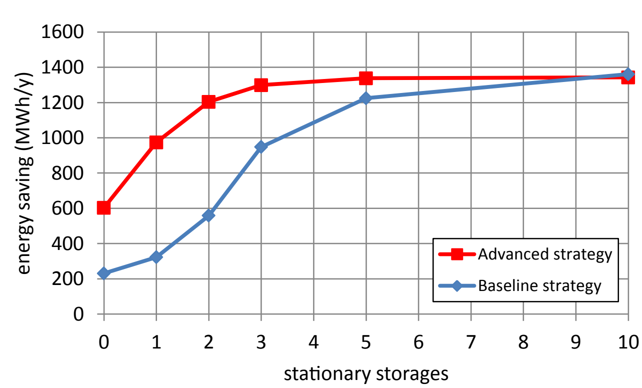

Fig. 11. Energy saving trend versus number of stationary storage units installed.

Table 7
Main characteristics of the considered supercapacitor stack.

Supercapacitor stack	
Nominal cell capacitance (F)	3000
Nominal cell voltage (V)	2.7
Max cell voltage (V)	2.85
Min cell voltage (V)	1.4
Peak current (A)	2000
Number of cells in series	350
Number of cells in parallel	6
Cell mass (kg)	0.5
Stack mass (kg)	1260

As visible, the energy saving guaranteed by the advanced control is comparable to that obtained by the installation of two storage systems, with the baseline control. Furthermore, with equal number of storages, in case of *advanced control* the energy saving is three times respect to the *baseline control* using one storage, two times using two storages, around 1.4 times with three.

The saturation of energy saving as a function of the number of storage units can be easily interpreted considering voltage drop along the contact line caused by the flow of the recovered current.

Indeed, for the system under consideration the line resistance is such that the maximum recovered current (around 1000 A) causes a voltage drop of 145 V along a distance of 1.0 km. Therefore recovery of energy through distances larger than 1.0 km becomes more and more ineffective, since the recovered current becomes lower and lower due to the voltage limit at the pantograph.

To make this consideration systematic, we define that the average distance *train-to-ESS* should not overcome the "effective reach", that can be defined as:

- For the *baseline control*, the distance at which the maximum recovered current causes a voltage drop equal to $U_{max} - U_{nom}$, after that the recovered current is stopped. With our value $U_{max} = 900$ V and $U_{nom} = 750$ V, this distance is around 1.0 km.
- For the *advanced control*, twice the distance at which the maximum recovered current causes a voltage drop equal to $U_{max} - U_{nom}$, at which the braking current is around half the maximum recovered current. In fact, with our value $U_{max} = 900$ V, at a distance of 2.0 km from an ESS operating at $U_{nom} = 750$ V the maximum current that can be recovered is 517 A.

Consequently to the average distance *train-to-ESS* previously defined, the minimum recommended *storage-to-storage* distance is therefore twice the "effective reach". This means that:

- For the *baseline control*, the minimum recommended *storage-to-storage* distance is around 2.0 km.
- For the *advanced control*, the minimum recommended *storage-to-storage* distance is around 4.0 km.

Given that the line considered has a length of 12 km, this analysis is in agreement with the results of Fig. 11. In fact the saturation takes place, in case of *baseline control*, over five storages equally spaced; in the *advanced control*, over three storages.

3.3. Stationary systems based with supercapacitors

Since braking times are in the order of 10–20 s, one of the most proposed solution takes advantage of super-capacitors. The main characteristics of the considered supercapacitor stack are shown in Table 7. The rated capacitance, the window voltage, the maximum allowed current are taken from available products. The inner resistance comes from experimental tests, already cited in the previous section. The number of elements has been chosen to stay within the recommended maximum current limits, and to maintain the SOC within the desired band.

The peak currents obtained in the worst case, corresponding to the rush hour configuration (10 trams) with one storage system installed, are shown in Fig. 12 (top). They are compatible with the cell's characteristics. As visible in Fig. 12 (bottom), the SOC oscillation covers the 70% of the total available voltage window. Moreover, the proposed usage of supercapacitors is compatible its expected cycle life, that is about one million of full charge–discharge cycles.

Advantages in terms of energy saving can be compared with the lithium battery configuration: the differences are mainly due to the overall charging/discharging energy efficiency, and due to the allowed current limits managed by the DC/DC converter, at unmodified requests from the load. Table 8 matches results of hourly

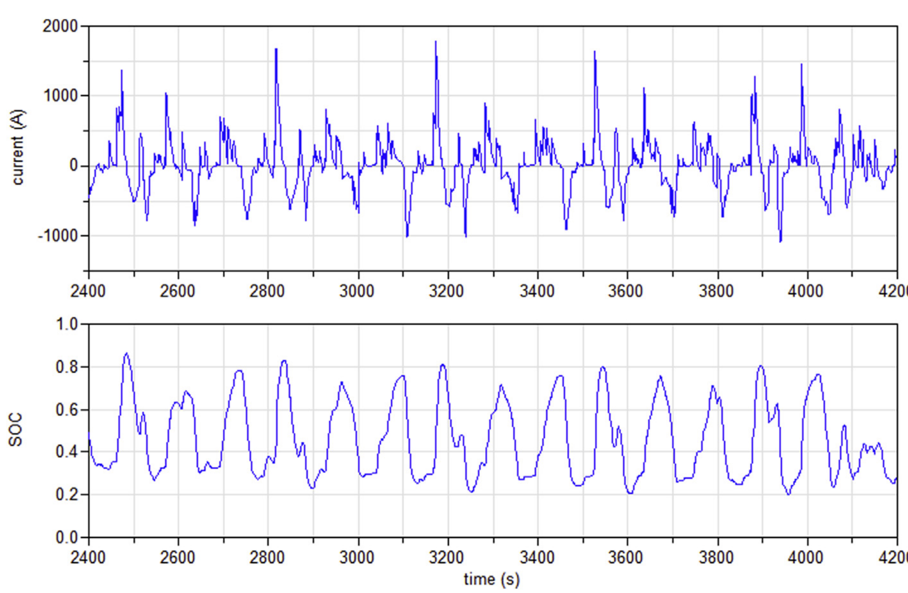

Fig. 12. Supercapacitor current (top) and SOC (bottom) during a portion of a rush hour.

Table 8
ESSs energy, recovered energy.

Case	Lithium battery		Supercapacitor	
	Total ESS energy (MWh/h)	Recovered energy (MWh/h)	Total ESS energy (MWh/h)	Recovered energy (MWh/h)
C-1 rush hours	0.822	0.548	0.853	0.505
C-1 low load hours	0.324	0.188	0.327	0.182
C-1 holidays	0.167	0.107	0.170	0.101

energy consumptions in case of one storage system installed, respectively, during rush, low load and holidays hours. Results are referred to the advanced control.

It is apparent that the maximum hourly difference in terms of ESSs energy between the lithium battery and the supercapacitor based solutions occurs during rush hours and is around 3.5%, while the minimum, in correspondence of holiday hours, is not higher than 1.5% .

Annual energy saving, obtainable as weighted average of hourly consumptions, are therefore almost equivalent between the two storage configurations.

3.4. On-board systems based with high power lithium batteries

3.4.1. Configuration with the DC/DC converter

The installation of the stationary storage systems has the main drawback that the braking energy must flow along the catenary, subjected to losses and corresponding voltage drop. These problems can be mitigated, as already described, by the installation of a pretty large number of storage systems.

An alternative solution is to install the storage systems directly on board trains. This solution aims to completely avoid the problem of the voltage drop on the line, and therefore the subsequent problems of cutting the rise voltages. Additionally, the storage has to manage only the load requests from the tram in which is installed, thus avoiding the need to receive or deliver over currents from other trams.

On the other hand, this solution requires higher costs due the need to install the storage system on-board all trains, with further disadvantages in terms of space occupation and mass increment, about 1.2 tonnes, and resulting increase of energy consumptions.

The storage system already described in Table 5 is adopted, to ease comparison with the stationary solution. For the reason already explained, the DC/DC converter is included. Fig. 13 shows the input and output DC/DC voltage (top), the current from the battery pack on-board one single tram (middle), with its corresponding velocity profile (bottom).

Comparing with the plot of Fig. 10, it is clearly visible that the battery pack does not receive extra current peaks, since it has only to deliver or receive currents from the single tram in which is installed. In fact, the current does not overcome the limit of 1000 A, as in the stationary system.

3.4.2. Energy saving

Energy saving has been evaluated also in case of on-board storage systems, taking as reference conditions already shown in Paragraph 3.2.3, and compared to those obtained for stationary storage systems, as visible from Table 9. The following remarks can be done:

- Energy saving is naturally enhanced respect to the standard configurations without storage systems (A, B).
- The recovered energy for on-board configurations is increased respect to the stationary ones.
- The ESS energy is enhanced, due the rise of energy consumption for the increased masses.

As a consequence, the configuration characterised by ten on-board storage systems (C-10 on-board in Table) is roughly equivalent to the three stationary ones (C-3 stationary), in the case of the advanced control.

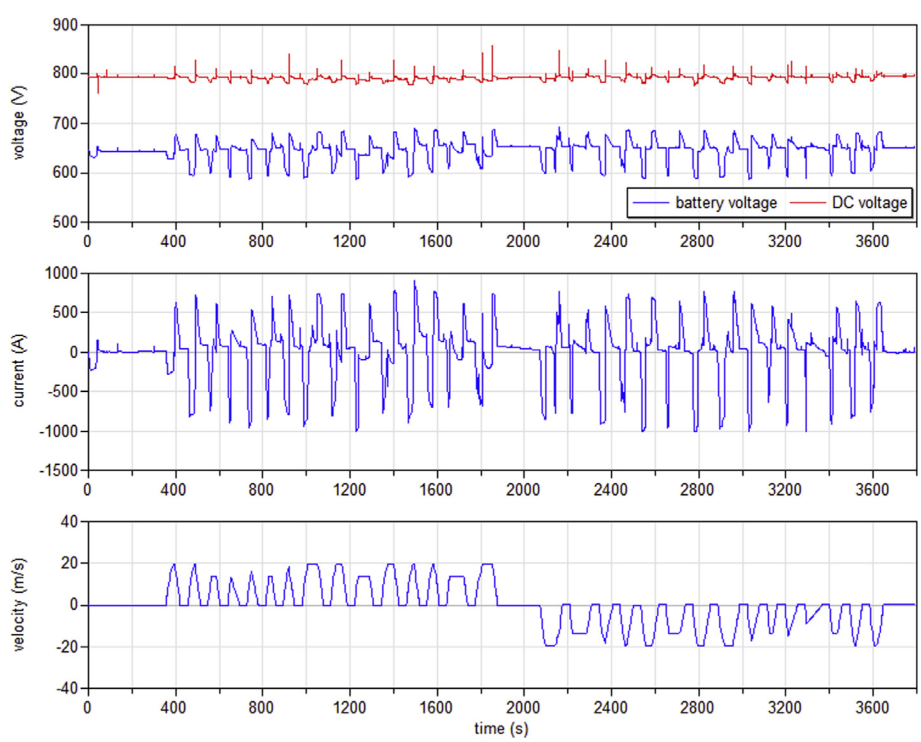

Fig. 13. Battery current (top), voltage (middle) and train speed (bottom) during a portion of rush hour.

Table 9
ESSs energy, recovered energy, energy saving.

Case	Total ESS energy (MWh/y)		Recovered energy (MWh/y)		Energy savings (MWh/y)	
	Baseline control	Advanced control	Baseline control	Advanced control	Baseline control	Advanced control
A	3100		0		–	
B	2869	2497	206	742	231	603
C-1 stationary	2777	2126	394	1280	323	974
C-3 stationary	2152	1801	1156	1590	948	1299
C-3 on-board	2230	1847	1086	1571	870	1253
C-10 stationary	1739	1757	1508	1614	1361	1343
C-10 on-board	1812		1622		1288	

The type of control has no effect in case of on-board installation of the RESS, since the voltage never reaches its maximum value of 900 V, as visible always from Fig. 13.

Another case of interest is the on-board installation of RESS on a reduced number of trains, maintaining the others unmodified. The number, by analogy with one of the most promise stationary cases under study, has been chosen equal to three. Strengths and weakness already mentioned are in this case mitigated respect to the full on-board installation. It must also be said that for this mix situation, since the voltage sometimes reaches the value of 900 V maximum value (i.e. when the train without storage on-board is very far respect to the trains equipped with storage), the difference between the two braking adopted strategies comes back to be significant.

Furthermore, Fig. 14 shows the trend of the energy saving versus the number of trains equipped with the on-board storage units. As visible, with ten units installed, the energy saving strongly increases, up to a saturation level. It is also apparent that the difference between the two strategies is almost constant, moving from one to the three storages configuration.

3.5. On-board systems based with supercapacitors

The final case can be easily interpreted having as reference the results already detailed in the previous sections. The supercapacitors stack is the same defined for the stationary application, detailed in Table 7.

Respect to the lithium battery solution, in terms of DC/DC setting, no any limitation of current has been considered, allowing the SC peaks of current up to 2000 A.

In this case the difference in terms of hourly ESSs energy in case of supercapacitor or lithium battery, under equal number of storages, differs less than 1% (Table 10).

4. Cost/benefit analysis

The considered scenario refers to private and public transport companies wishful to upgrade their plants. The standard systems normally allow to recover part of the braking energy amongst trams, also without the installation of a storage system. For these reasons, the standard scenario has been identified in the case B previously mentioned. In line with the previous part of the activity, both the baseline and the advanced energy recovery strategies were considered. It must in fact be said, although the most common technology refers to the baseline control, that both the technologies could be used on existing plants.

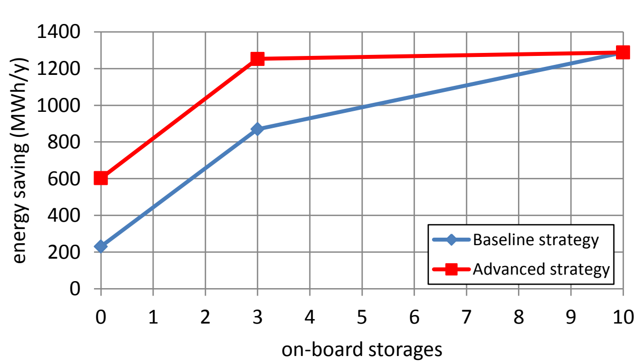

Fig. 14. Energy saving versus number of on-board storage units installed.

The cost analysis mainly takes into account the following parameters:

- The initial cash outlay on the purchase of the storage system and the power converter, the balance of plant included.
- The Annual saving from the simulated ESSs energy, compared to that one obtained in the standard configuration (case B).

More in detail, the following costs criteria have been chosen:

- About LFP battery, a value of 500 €/kWh has been considered including cells, BMS, battery packaging. The same price is used both for stationary and mobile application.
- About the supercapacitors, a value of 0.02 €/F has been chosen. It includes also the cost for assembling the stack.
- An additional amount of 10% is considered, to take into account the balance of plant.
- For each DC/DC converter a fixed price of 20 k€ is considered.
- The corresponding money advantage, considering the current industrial user prices of energy in Italy, was evaluated considering an average value of 150 €/MWh.
- In terms of maintenance costs, for the reason explained in previous sections, both supercapacitors and high power lithium batteries are able to cover the whole life of the plant, estimated in ten years.

The main objective of the analysis was related to the identification of the payback time of the investment.

The situation that identifies the best case, in which the company makes use of a standard system (case B) characterised by the advanced control, is detailed in Table 11. The results of Table 11 can be interpreted as follow:

Table 10
ESSs energy, recovered energy.

Case	Lithium battery		Supercapacitor	
	Total ESS energy (MWh/h)	Recovered energy (MWh/h)	Total ESS energy (MWh/h)	Recovered energy (MWh/h)
C-10 on-board rush hours	0.746	0.633	0.741	0.627
C-10 on-board low load hours	0.274	0.250	0.273	0.248
C-10 on-board holidays	0.146	0.132	0.146	0.132

Table 11
Cost/benefit analysis, advanced control.

Case	Typology	Cash outlay (k€)	Annual saving (k€)	Payback time (*y*)
C-1 stationary	Li-bat	73.5	62.0	*2*
C-1 stationary	SC	158.6	55.7	4
C-3 stationary	Li-bat	220.5	104.4	3
C-3 stationary	SC	475.8	97.2	6
C-3 on-board	Li-bat	220.5	97.5	*3*
C-3 on-board	SC	475.8	90.6	7
C-10 on-board	Li-bat	735.0	102.8	9
C-10 on-board	SC	1586.0	104.4	18

The numbers in italics indicate the lower payback time for the considered case (i.e. stationary or on-board).

- The installation of one single stationary storage system gives the most reduced payback time. In fact the extra energy saving obtained with the three storages configuration is not able to compensate, in the same time, the costs of other two additional storage systems.
- The on-board configuration seems not able to guarantee significant advantages. For a limited number of trains, payback times are aligned to the stationary, equivalent variants. It must also be said that cash outlay is considered equal both for stationary and mobile applications: this approximation is acceptable mainly considering the design of totally new trams; on the contrary, an additional cash outlay should be considered, in case of updating the already existing ones.
- When the installation on-board regards all the trams, payback times are very large, especially for the supercapacitor solution.
- The choice of using supercapacitors instead of lithium batteries seems not to be competitive, mainly for the higher cash outlay. More advanced control strategies could also allow to slightly reduce the sizing of the SC stack, while however limiting the amount of the recovered energy. On average, SC payback times are around twice those of battery solution for all the analysed configurations.

The worst-case situation, in which the company uses a standard system (case B) equipped with the baseline control, is detailed in Table 12. Table 12 can be interpreted as follow:

- The installation of one stationary storage system does not have the beneficial impact of the previous case. As noticeable from Fig. 11, the energy saving increases slowly in the first part of the curve, mainly because the installation of one single storage system is not able to limit the voltage increases over 900 V.
- The installation of three storage systems, both for the stationary and the on-board configuration, brings the benefits of the previous solution: the payback time remains therefore around three years.
- The usage of supercapacitors, here omitted for compactness, shows payback times around two times those already evaluated for the lithium battery based solutions, as for the previous case.
- The installation of the storages on-board all the trains produces much more energy saving that in the previous case: this is visible also from the payback time, that is reduced of about three years.

Table 12
Cost analysis, baseline control.

Case	Typology	Cash outlay (k€)	Annual saving (k€)	Payback time (*y*)
C-1 stationary	Li-bat	73.5	13.8	7
C-3 stationary	Li-bat	220.5	107.6	*3*
C-3 on-board	Li-bat	220.5	88.4	*3*
C-10 on-board	Li-bat	735.0	158.6	6

The numbers in italics indicate the lower payback time for the considered case (i.e. stationary or on-board).

5. Conclusions

- Implementation of braking energy recovery in the considered tramline allows important energy saving even in case no storage system is installed: the recovered energy is exploited by other trains that are accelerating or running. Important increases in saving can be obtained if the control logic of the energy recovery is such that even when the highest allowable catenary voltage is reached, some partial energy flow from the train to the catenary is maintained.
- The energy saving can be by large increased if some storage systems are installed: depending on the line resistance, there is a maximum reach to which the recovered energy can be effectively sent. Therefore the greatest advantages are obtained if several storage systems are installed along the line. In the considered case the storage systems are effective only up to a distance from each other of around twice the effective reach of each ESS, i.e. 2 km for the *baseline control*, and 4 km for the *advanced* one.
- The storage systems can be directly connected to the line, or a DC/DC converter can be put between. The latter solution allows better managing the storage systems, reducing their stress and avoiding SOC deviations. On the other hand, it involves reductions in energy saving because of their inner losses, and higher initial cost.
- From the cost/benefit point of view, the stationary systems represent the best choice.
- The optimal number of storages to be installed depends on the adopted control. In our case, the lowest payback time is obtained installing three RESSs for the *baseline control*, one RESS for the *advanced* one. Both results are in agreement with the minimum recommended *storage-to-storage* distance previously evaluated, and show how payback time evaluation might lead to different assessments respect to those obtainable merely from the energy saving analysis.
- The supercapacitors are disadvantages in terms of initial cash outlay. On the contrary, the high power lithium batteries appear much more competitive, since they show equivalent performance and, as for the supercapacitors, do not require to be replaced within the useful life of the plant.

Since all results were obtained using real-life traffic conditions, they are a good indication of what could happen also in other, similar, urban railroads.

References

[1] A. González-Gil, R. Palacin, P. Batty, J.P. Powell, Energy Convers. Manag. 80 (2014) 509–524.
[2] A. González-Gil, R. Palacin, P. Batty, Energy Convers. Manag. 75 (2013) 374–388.
[3] R. Teymourfar, B. Asaei, H. Iman-Eini, R. Nejati fard, Energy Convers. Manag. 56 (2012) 206–214.
[4] L. Mir, I. Etxeberria-Otadui, I. Perez de Arenaza, I. Sarasola, T. Nieva, in: Energy Conversion Congress and Exposition, 2009, pp. 1632–1639. http://dx.doi.org/10.1109/ECCE.2009.5316073.
[5] P. García, J.P. Torreglosa, L.M. Fernández, F. Jurado, Int. J. Hydrogen Energy 37 (2012) 9368–9382.
[6] P. García, L.M. Fernández, J.P. Torreglosa, F. Jurado, Comput. Electr. Eng. 39 (2013) 1993–2004.
[7] Modelica Association official site (http://www.modelica.org).
[8] P. Fritzson, Introduction to Modeling and Simulation of Technical and Physical Systems with Modelica, Wiley-IEEE Press, 2011.
[9] P. Fritzson, P. Aronsson, A. Pop, H. Lundvall, K. Nystrom, L. Saldamli, D. Broman, IEEE Computer Aided Control System Design, 2006, pp. 1585–1595. http://dx.doi.org/10.1109/CACSD-CCA-ISIC.2006.4776878.
[10] M. Ceraolo, G. Lutzemberger, M. Funaioli, P. Bolognesi, S. Barsali, in: Second International Conference on Railway Technology: Research, Development and Maintenance (Railways 2014), Ajaccio (Corsica), 8–11 April 2014.

[11] R. Marconato, Electric Power Systems, Italian Electrotechnical Committee (CEI), 1, Sez. 6.2, ISBN: 88-432-0014-3.
[12] M. Ceraolo, M. Conte, R. Giglioli, G. Lutzemberger, M. Pasquali, in: AEIT Annual Conference, Mondello (PA), 3–5 Oct. 2013. http://dx.doi.org/10.1109/AEIT.2013.6666810.
[13] M. Ceraolo, IEEE Trans. Power Syst. 15 (2000) 1184–1190.
[14] S. Barsali, M. Ceraolo, IEEE Trans. Energy Convers. 17 (2002) 16–23.
[15] M. Ceraolo, G. Lutzemberger, T. Huria, SAE Tech. Pap. (2011), 2011-01-1365, http://dx.doi.org/10.4271/2011-01-1365.
[16] E. Tironi, V. Musolino, in: International Conference on Clean Electrical Power, 2009, pp. 376–382. http://dx.doi.org/10.1109/ICCEP.2009.5212028.
[17] M. Ceraolo, M. Funaioli, G. Lutzemberger, M. Pasquali, D. Poli, L. Sani, in: Second International Conference on Railway Technology: Research, Development and Maintenance (Railways 2014), Ajaccio (Corsica), 8–11 April 2014.
[18] Kokam Battery official site (http://www.kokam.com/new/kokam/sub01/sub01_01.html).
[19] M. Ceraolo, G. Lutzemberger, M. Marracci, in: IEEE Vehicle Power and Propulsion Conference (VPPC, 1–3 Sept. 2010. http://dx.doi.org/10.1109/VPPC.2010.5729096.
[20] A123 Systems official site (http://www.a123systems.com/solutions-transportation-passenger-vehicles.htm).